LODZ UNIVERSITY OF TECHNOLOGY
FACULTY OF ELECTRICAL, ELECTRONIC,
COMPUTER AND CONTROL ENGINEERING
INSTITUTE OF APPLIED COMPUTER SCIENCE

Abstract of Ph.D. Thesis

Real-Time Ultrasound images filtering using graphics processing units (GPU)

MSc. Paweł Zajączkowski
Department of Mathematics and Informatics, University of Lodz,
22 Banacha street, 90-238 Lodz, Poland
zajaczkowski.pawel@math.uni.lodz.pl

supervisor:
Prof. D.Sc. eng. Mariusz Nieniewski

Lodz 2016 A.D.

The US imaging is a common diagnostic tool used all over the world. However, the US images have some limitations due to the fact that they are covered with bright speckles. In reality, the speckle removal is a fundamental problem of ultrasound imagery and there exist many algorithms that solve this problem [8]. The most refined methods are those based on the diffusion, such as the NCD [1]. By executing the computations in the GPU rather than CPU, one can significantly reduce the processing time of medical images [6], [7]. In order to achieve the main scientific goals of the thesis: **Real-time effective ultrasound images filtering is possible using parallel computing on GPU**, the author has implemented and experimentally verified the following GPU-designed and developed measurement data processing algorithms:

- Real-Time Speckle Reduction in Ultrasound Images by Nonlinear Coherent Diffusion Using GPU
- Real-Time Ultrasound Image Enhancement by FBD Using GPU
- Ultrasound Image Despeckling Using Non-Local Means with Diffusion Tensor
- Comparison of ultrasound image filtering methods by means of multivariable kurtosis

The above formulated thesis has been proved successfully. Furthermore, the most important results and conclusions are presented.

The disertation describes a novel GPU implementation of the nonlinear coherent diffusion (NCD) algorithm for speckle reduction in ultrasound (US) images. Although the NCD algorithm provides satisfactory results, its execution in the CPU is too slow for real-time applications typical for US images.

The use of parallel computing in the GPU allowed us to reduce the processing time of a single iteration of the diffusion to 85.8 ms for an image of size $512 * 1024$ pixels.

The obtained results confirm that there is a considerable reduction of the computation time, even with an average NVIDIA card of the GeForce GT 650M type in the Dell Inspiron 7720 computer, when compared with the Matlab program optimized for the sequential operation for the same computer. As a result the NCD algorithm has a potential for being used in US equipment. It is worth mentioning that testing the algorithm with 25 various images showed that the respective diffused images obtained with double precision arithmetic in CUDA and Matlab differed less than 1.54×10^{-9} in any pixel.

There exist many algorithms for speckle removal as described in the book [8] and the review paper [3]. One of the best despeckling methods is the NCD [1]. However, the careful examination of the effects of this method reveals that the quality of the filtered images might be further improved [11] and this can be done with the FBD algorithm that is inherently faster than the NCD. The forward-backward diffusion (FBD) can be used for edge improvement in any image. The case considered in this paper is that of ultrasound (US) images. The US images are imperfect since the useful signal representing anatomical details is obscured by speckles inherent in this approach. A method such as the nonlinear coherent diffusion (NCD) can remove speckles to a large extent. However, the NCD-processed image can be further enhanced by the FBD. My disertation describes the details of the proposed GPU implementation of the FBD algorithm. The obtained execution time of one iteration of the FBD algorithm is less than 2.2 ms for a 1024×1024 image.

The NLM is one of the image despeckling methods and is originally presented in [2]. Subsequently, several important modifications of this method were developed. In particular, in [4] a Bayesian framework is used to derive a NLM algorithm adapted to the US image noise model. In [10] the anisotropic NLM algorithm is proposed for general images. In [12] the NLM filter which employs structural similarity index instead of Euclidean distances in the calculation of the weights used in the NLM filter is presented. In [13], Wu developed a modification of the classic NLM in which the Euclidean distance between the brightness vectors used in the calculation of the weights was replaced by the structure tensor taking into account specifically the possibility of occurrence of edges in the image.

My disertation presents a novel modification of one of the varieties of the non-local means (NLM) algorithm for speckle reduction in ultrasound (US) images. This modification comes in the form of replacement of the structure tensor used in the NLM algorithm by the diffusion tensor. The diffusion tensor was originally used in the nonlinear coherent diffusion making possible the intensification of the diffusion in the direction parallel to edges and inhibition in the direction perpendicular to edges. It is shown in the paper that using the diffusion tensor in calculating the weights for the NLM leads to an improvement of quality of despeckled images. The NLM algorithm has a tendency to smoothen the image in such a way that the despeckled image is covered by relatively flat areas typical for mosaic images. This tendency is undesirable since flat areas form visible contours that are not related to the human tissues under investigation. The superiority of the new despeckling filter is confirmed by the presented examples of the filtering as well as by image quality measures.

Replacing the structure tensor by diffusion tensor in calculating the weights used in the NLM results in the improvement of the despeckled images. The superiority of the proposed method over the NLM with structure tensor is confirmed by both visual inspection and calculation of several image quality measures.

Comparison of the quality of despeckled US images is complicated because there is no reference image of human body which would be free of speckles and could serve for comparisons. As a result, dozens of features are proposed in the literature for describing some aspects of the image quality, but their totality does not simply indicate which image is better and which is worse. The current disertation proposes the use of the multivariate kurtosis for the evaluation of the most important edges in an image. It turns out that the kurtosis allows one to introduce some kind of order among the filtered images which can be used for image quality evaluation. The disertation presents a numerical procedure for calculating the kurtosis and describes detailed results of calculating the kurtosis for a simulated image, phantom images, and a real-life image. 16 different methods of image despeckling are compared via kurtosis. The disertation shows that the kurtosis generally increases when an image is despeckled, and visually more satisfactory despeckling results can be associated with higher kurtosis. In particular, the iterative smoothing of the image by means of nonlinear coherent diffusion proportionally increases kurtosis for successive iterations. To summerize, kurtosis ideals with only one aspect of images and should not be used as a global measure of image quality.

In my disertation, the use of multivariable kurtosis for comparison of US image despeckling methods is proposed. Kurtosis is a highly nonlinear function whose behavior can be observed best by conducting numerical experiments rather than theoretical considerations. The advantages of the use of kurtosis have been illustrated by examples including computer generated images, images of phantoms as well as natural images. A number of despeckling filters have been tested. The main conclusion is that despeckling leads to an increase of the multivariable kurtosis. This increase for a given input image improves the subjective assessment of the quality of the filtered image. Multiiterative filtering, such as in the case of NCD, results in an approximately proportional increase of kurtosis. Once the speckles have been completely removed, one can sharpen the edges by 'a touch' of the FBD. In this case the tissue's edges become steeper and kurtosis decreases. In order to have more pronounced numerical results it is recommended to calculate the average of local kurtosis values over a number of frames covering the most interesting edges in the image. It has been found that using frames of size 8×8 and transforming these frames into their Fourier counterparts gives meaningful results that can be used for assessing the despeckling effects. In summary, multivariable kurtosis can be included as one of the features used for comparison of the despeckling filters, for example Loizou2014: geometric average error, mean square error, signal to noise ratio, root mean square error, peak signal to noise ratio, Err3 and Err4 Minkowski metrics, universal quality index, structural similarity index, average difference, structural content, normalized cross correlation as well as maximum difference.

It is worth noting that the use of the multivariate kurtosis is not restricted to medical images. In fact, it can be used for any US images as well as for any other images contaminated with speckle noise, for example radar images.

In summary, the scientific goal of PhD thesis was achieved, and the thesis was proved.

References

[1] Abd-Elmoniem, K.Z., Youssef, A.B.M., Kadah, Y.M.: Real-time speckle reduction and coherence enhancement in ultrasound imaging via non-linear anisotropic diffusion. IEEE Trans Biomed Eng 49(9), s.997–1014 (2002).

[2] Buades, A., Coll, B., Morel, J. M.: A review of image denoising algorithm, with a new one. Multiscale Modeling and Simulation 4(2), s. 490–530 (2005).

[3] Contreras Ortiz, S.H., Chiu, T., Fox, M.D.: Ultrasound image enhancement: a review. Biomed Sign Proc & Control 7, s. 419–428 (2012).

[4] Coupe, P., Hellier, P., Kervann, C., Barillot, C.: NonLocal Means-based Spckle Filtering for Ultrasound Images IEEE Transactios on image processing, VOL. 18, NO. 10 (2009).

[5] Cruz, F. A.: Tutorial on GPU computing with an introduction to CUDA `http://lorenabarba.com/gpuatbu/Program_files/Cruz_gpuComputing09.pdf`.

[6] de Fontes, F.P.X., Barroso, G.A., Coupé, P., Hellier, P.: Real time ultrasound image denoising. Journal of Real-Time Image Processing 6, 15–22 (2011).

[7] Eklund, A., Dufort, P., Forsberg, D., LaConte, S.M.: Medical image processing on the GPU – past, present and future. Medical Image Analysis, 17, s. 1073–1094 (2013).

[8] Loizou, C.P., Pattichis, C.S.: Despeckle Filtering Algorithms and Software for Ultrasound Imaging. Morgan & Claypool (2008).

[9] Loizou, CP, Theofanus, C, Pantziaris, M., Kasparis, T.: Despeckle filtering software toolbox for ultrasoundimaging of the common carotid artery. Comp Methods Programs Biomed., vol. 114, s.109–124 (2014).

[10] Maleki, A., Narayan, M., Baraniuk, R. G.: Anisotropic nonlocal means denoising. Applied Comput. Harmonic Analysis (35) (2011).

[11] Nieniewski, M.: Enhancement of Despeckled Ultrasound Images by Forward-Backward Diffusion. In: ICCVG 2014. LNCS, vol. 8671, s. 454–461. Springer (2014).

[12] Rehman, A., Wang, Z.: SSIM-based non-local means image denoising. 18th IEEE International Conference on Image Processing (2011).

[13] Wu, X., Xie, M., Wu, W., Zhou, J.: Nonlocal means image denoising using anisotropic structure Tensor. Advances in Optical Technologies (2013).